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Asymmetries in the Production of Λ_c^+ and Λ_c^- Baryons in 500 GeV/c π^- Nucleon Interactions

Fermilab E791 Collaboration

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We present a measurement of asymmetries in the production of Λ_c^+ and Λ_c^- baryons in 500 GeV/c π^-–nucleon interactions from the E791 experiment at Fermilab. The asymmetries were measured as functions of Feynman x (x_F) and transverse momentum squared (p_T^2) using a sample of $1\,819 \pm 62$ Λ_c's observed in the decay channel $\Lambda_c^+ \to pK^-\pi^+$. We observe more Λ_c^+ than Λ_c^- baryons, with an asymmetry of $(12.7 \pm 3.4 \pm 1.3)$ % independent of x_F and p_T^2 in our kinematical range ($-0.1 \leq x_F \leq 0.6$ and $0.0 \leq p_T^2 \leq 8.0$ (GeV/c)^2). This Λ_c asymmetry measurement is the first with data in both the positive and negative x_F regions.

Several studies [1] have reported an enhancement in the production rate of charm particles having a valence quark or diquark in common with the incident particles, relative to charge-conjugate particles which have fewer or no common valence quarks. This effect, known as the leading-particle effect, cannot be accounted for by next-to-leading-order perturbative QCD (pQCD) calculations followed by Peterson fragmentation of the produced c and $\bar{c}$ quarks. Thus, the effect is attributed to additional hadronization effects or non-pQCD contributions to charm production.

In this work we report on the $\Lambda_c^+ - \Lambda_c^-$ production asymmetry measured using a sample containing $1\,819 \pm 62$ fully-reconstructed $\Lambda_c^+ \to pK^-\pi^+$ and charge conjugate (c.c.) decays from the Fermilab E791 experiment. The data are from 500 GeV/c π^--nucleon interactions. This measurement represents a significant increase in statistics from previously published results, and it also explores for the first time the production asymmetry at negative values of x_F. This feature of our measurement allows us to look both for diquark effects which should be present in the negative x_F region (since the Λ_c^+ has two valence quarks in common with the target particles whereas the Λ_c^- has none) and for leading particle effects in the positive x_F region (in which both the particle and antiparticle share a single valence quark with the incident pions). The production asymmetries are measured as functions of x_F and p_T^2 in the kinematic ranges $-0.1 \leq x_F \leq 0.6$ and $0 \leq p_T^2 \leq 8$ (GeV/c)^2.

Varied predictions about what asymmetries should be observed in the E791 data are made by three models which address leading particle effects: the string fragmentation (SF) model [2], the intrinsic charm (IC) model [3], and the two-component recombination (2CR) model [4].

In the string fragmentation model implemented in the Lund PYTHIA/JETSET package [5], the c and $\bar{c}$ quarks produced by leading order QCD diagrams are connected by color strings to valence quarks or diquarks in the beam or target particles. Hadronization proceeds through fragmentation of the ends of the color string and recombination with valence quarks from the initial particles. The model predicts a negative asymmetry (more Λ_c^- than Λ_c^+) for $x_F > 0$, a positive asymmetry for $x_F < 0$, and a flat dependence on p_T^2.

For the intrinsic charm model, fluctuation of one or the other of the incident particles to a Fock state containing $c\bar{c}$ quarks ($|uudc\bar{c}\rangle$ or $|uddc\bar{c}\rangle$ for nucleons and $|\bar{u}dc\bar{c}\rangle$ for π^-) favors production of particles with valence quarks in common with the Fock state via a coalescence (recombination) mechanism. Hence, this model predicts no asymmetry in the $x_F > 0$ region and a positive asymmetry for $x_F < 0$, increasing as one moves toward more negative x_F.

In the two-component recombination model, hadronization takes place through fragmentation of perturbatively produced c and $\bar{c}$ quarks, and the recombination of valence and c ($\bar{c}$) quarks produced in the initial collision. In the $x_F < 0$ region, this model predicts a positive asymmetry growing strongly as x_F becomes more negative, due to target-diquark effects. Again, there is no asymmetry in the pion fragmentation region ($x_F > 0$) since both Λ_c^+ and Λ_c^- are singly-leading particles.

The main difference between the IC and 2CR models is that the former predicts very little asymmetry in the E791 negative x_F range because the IC distribution peaks at about 0.6 of the initial particle momentum. Because of diquark effects, the 2CR model can account for larger asymmetries in this region.

Neither the IC nor the 2CR model has been used to make a prediction regarding the variation of asymmetry with respect to p_T^2. Whatever asymmetries do exist, however, are expected to decrease as p_T^2 increases, since the density of beam and target valence quarks available for recombination decreases with increasing p_T^2.

Experiment E791 recorded data from 500 GeV/c π^- interactions in five thin foils (one platinum and four diamond) with center-to-center separations of about 15 mm. Each foil was approximately 0.4% of a pion interaction length thick (0.5 mm for the platinum foil and 1.6 mm for the carbon foils). The E791 spectrometer [6] in the Tagged Photon Laboratory was a large-acceptance, two-magnet spectrometer with eight planes of multiwire proportional chambers (MWPC) and six planes of silicon microstrip detectors (SMD) placed upstream of the target for beam tracking. Downstream of the target were 17 planes of SMD's for track and vertex reconstruction, 35 drift chamber planes, two MWPC's, two multicell threshold Čerenkov counters, electromagnetic and hadronic calorimeters, and a muon detector. The experiment recorded 2×10^{10} interactions using an open transverse-energy trigger and a fast data acquisition system [7].

A sample of candidate $\Lambda_c^+ \to pK^-\pi^+$ and c.c. decays was selected using similar criteria to those reported in Ref. [8]. Since the mean decay length for Λ_c's was several mm, in most cases they decayed in air gaps between the target foils and before entering the silicon vertex detectors. We selected all combinations of three tracks which had Čerenkov counter identification probabilities consistent with the $pK\pi$ hypothesis and which had a $pK\pi$ invariant mass between 2.15 and 2.45 GeV/c^2. We then required that the distance between the reconstructed candidate Λ_c decay vertex and the production vertex be at least five times the rms uncertainty in that distance. To further reduce background, we required the Λ_c to decay a distance greater than $5\sigma_L$ from the nearest material, where σ_L is the uncertainty on the vertex z position. The vertex position is also required to lie between one and four Λ_c lifetimes from the primary (interaction) vertex. The Λ_c momentum vector, reconstructed from its decay products, was required to pass within $50\,\mu m$ of the production vertex, and the reconstructed production and decay vertices were each required to have an acceptable χ^2. We also required that no more than one of the Λ_c-candidate decay tracks be consistent with coming from the primary interaction point. The sum of the p_T^2 of the secondary tracks with respect to the flight path of the reconstructed Λ_c was required to be greater than 0.35 (GeV/c)^2 if $-0.1 \leq x_F \leq 0.3$, and greater than 0.32 (GeV/c)^2 if $0.3 < x_F \leq 0.6$.

Events were kept if the Λ_c candidate had $-0.1 \leq x_F \leq 0.6$ and $p_T^2 \leq 8$ (GeV/c)^2. The $pK\pi$ invariant-mass plots for the final Λ_c^+ and Λ_c^- samples are shown in Figs. 1(a) and (b) respectively for $x_F < 0$, and in Figs. 1(c) and (d) for $x_F > 0$. Fits to a Gaussian signal and a quadratic background yield $1\,025 \pm 45$ $\Lambda_c^+ \to pK^-\pi^+$ and 794 ± 42 $\Lambda_c^- \to \overline{p}K^+\pi^-$ in the entire x_F and p_T^2 range.

For each bin of x_F or p_T^2 we define an asymmetry parameter A as

$$A \equiv \frac{N - \overline{N}/r}{N + \overline{N}/r} \;; \quad r = \frac{\overline{\epsilon}}{\epsilon} \tag{1}$$

where N ($\overline{N}$) is the number of Λ_c^+ (Λ_c^-) produced in the bin and the efficiency ϵ ($\overline{\epsilon}$) is the product of the geometrical acceptance and reconstruction efficiency for the bin.

Values for N ($\overline{N}$) were obtained from fits to $pK\pi$ invariant-mass distributions for events within specific x_F and p_T^2 ranges. In each case, well defined Λ_c signals were evident. Efficiencies (ϵ, $\overline{\epsilon}$) were calculated using a sample of 7×10^6 Monte Carlo (MC) events produced with the PYTHIA/JETSET event generator [5]. These events were projected through a detailed simulation of the E791 detector and then reconstructed with the algorithms used for the data. The final reconstructed MC sample was approximately ten times the size of our data sample. In the simulation of the detector, special care was taken to accurately simulate the reduced chamber efficiency seen in the experiment in a small region of the tracking chambers nearest the beam. The behavior of the apparatus and details of the reconstruction code changed during the data taking and data processing periods, respectively. To account for these effects, we generated the final MC sample in subsets mirroring these behaviors and combined the samples using their known fractional contributions to the data set. Good agreement between MC and data samples in a variety of kinematic variables and resolutions was achieved. The efficiency ratios obtained are shown in Fig. 2.

Acceptance-corrected asymmetries in the range $-0.1 \leq x_F \leq 0.6$ integrated over all $p_T^2 \leq 8$ (GeV/c)^2, and in the $p_T^2 \leq 8$ (GeV/c)^2 range integrated from -0.1 to 0.6 x_F, are shown in Fig. 3 and listed in Table 1. The statistical errors given include those due to the number of observed events and the number of MC events accepted. Typically, only for the highest x_F and p_T^2 bins is the error dominated by the MC uncertainty. Also shown in Fig. 3 are predictions from the default PYTHIA/JETSET . The asymmetries predicted by PYTHIA are negative for $x_F > 0$ and in all the p_T^2 range studied, while our data exhibit a positive asymmetry throughout the kinematical region studied. However, the data do not exclude a rise in the small negative x_F region.

Sources of systematic uncertainties were checked. Among them we checked the effect of changing the parametrization of the signal and background shape, the effect of varying our principal selection criteria and the effect of a 2.5 % K^- contamination in the beam.

The most significant effect comes from the parametrization of the background shape and the variation of our principal selection criteria. The effect of the K^- contamination in the beam, which might produce a negative asymmetry in the $x_F > 0$ region, was found to be negligible.

We also checked for contamination due to $D^\pm$ and $D_s^\pm$ decaying into $K\pi\pi$ and $KK\pi$ modes. We found that, by restricting our sample to have lifetimes between one and four Λ_c lifetimes, we reduced any possible contamination to negligible levels.

The SELEX collaboration has measured an asymmetry in the $x_F > 0.2$ region using different incident beam particles. Their preliminary results for the π^- beam indicate an asymmetry of $A = (25 \pm 15)\%$ [9]. The ACCMOR Collaboration [10] has also measured the $\Lambda_c^+ - \Lambda_c^-$ asymmetry over the $0 \le x_F \le 0.8$ region in 230 GeV/c π^-–Cu interactions and found $A = (0.5 \pm 7.9)\%$, indicating no asymmetry, although with large uncertainty. Our measurement, when averaged over the $0 \le x_F \le 0.6$ region, is $A = (12.3 \pm 3.7 \pm 1.6)\%$. No inconsistencies are observed in these results. The asymmetries measured by the three experiments and predictions of theoretical models are shown in Table 2.

In the forward x_F region, leading particle effects are expected to cancel since, in this region, both particle and anti-particle share one valence quark with incident pions. The observed constant asymmetry could be due to different energy thresholds for particle and antiparticle in associated production of charmed mesons and baryons. A similar effect was observed in the hyperon production asymmetries measured in this experiment [11]. Our data cannot exclude a rise in asymmetry in the $x_F < 0$ region. The default PYTHIA/JETSET model, which predicts a negative asymmetry over the range $x_F > 0$, does not provide a good description of our data. The data show a trend similar to predictions of the two component models [3,4].

We have presented data on Λ_c production asymmetries in both the forward ($x_F > 0$) and backward ($x_F < 0$) regions. The range of x_F covered, $-0.1 \le x_F \le 0.6$ allows the first simultaneous study of the Λ_c production asymmetry in both the negative and positive x_F regions. Our results show a uniform, positive asymmetry of $(12.7 \pm 3.4 \pm 1.3)$ % after acceptance corrections over the entire kinematical range studied .

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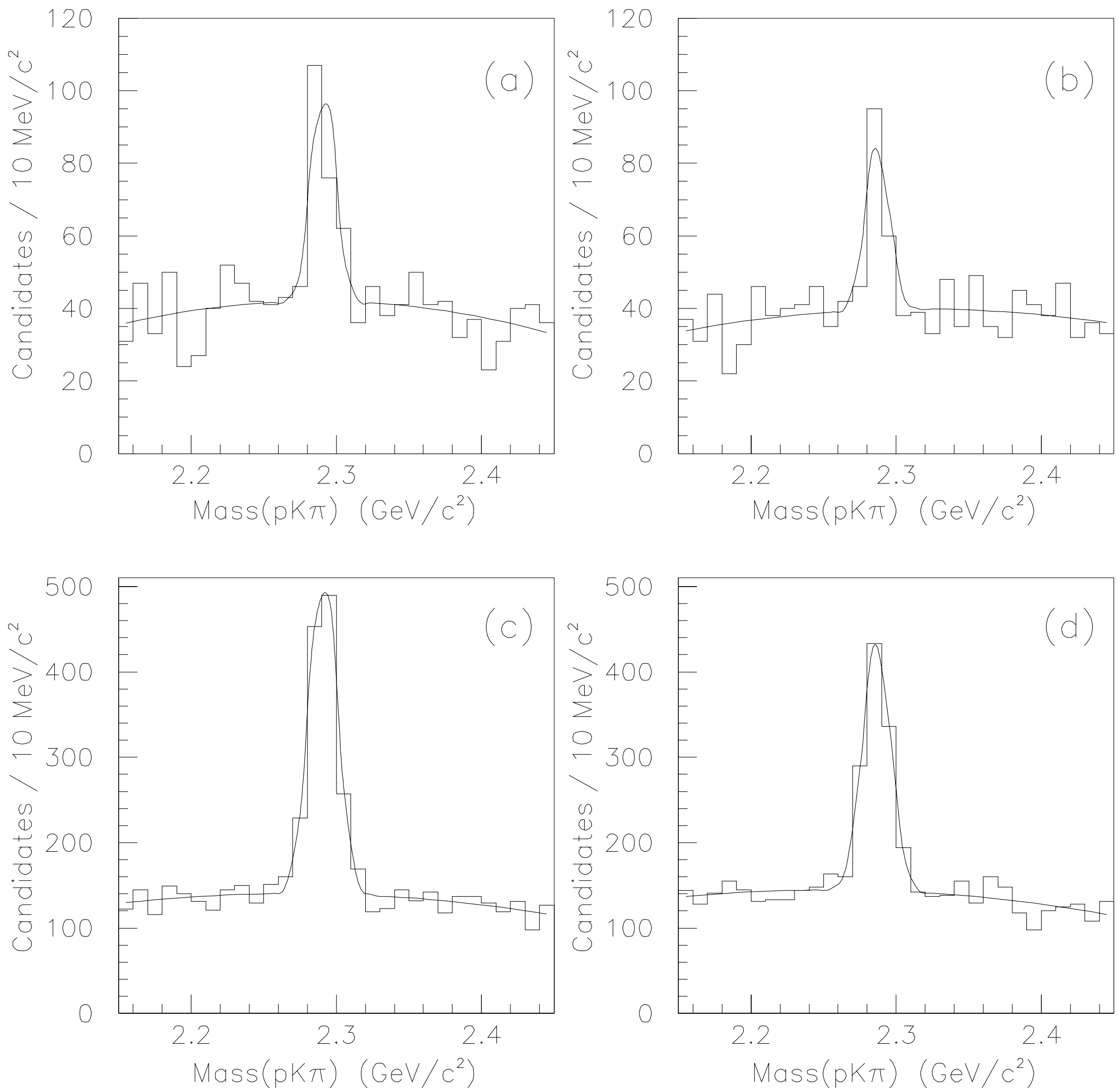


Figure 1. $pK^-\pi^+$ and $\overline{p}K^+\pi^-$ invariant-mass distributions for $x_F < 0$ and $x_F > 0$. All distributions show a clear Λ_c^+ and Λ_c^- signal. Fitting to a Gaussian signal and quadratic background yields 122 ± 17 Λ_c^+ (a) and 92 ± 15 Λ_c^- (b) in the negative x_F region and 903 ± 42 Λ_c^+ (c) and 702 ± 40 Λ_c^- (d) in the positive x_F region.

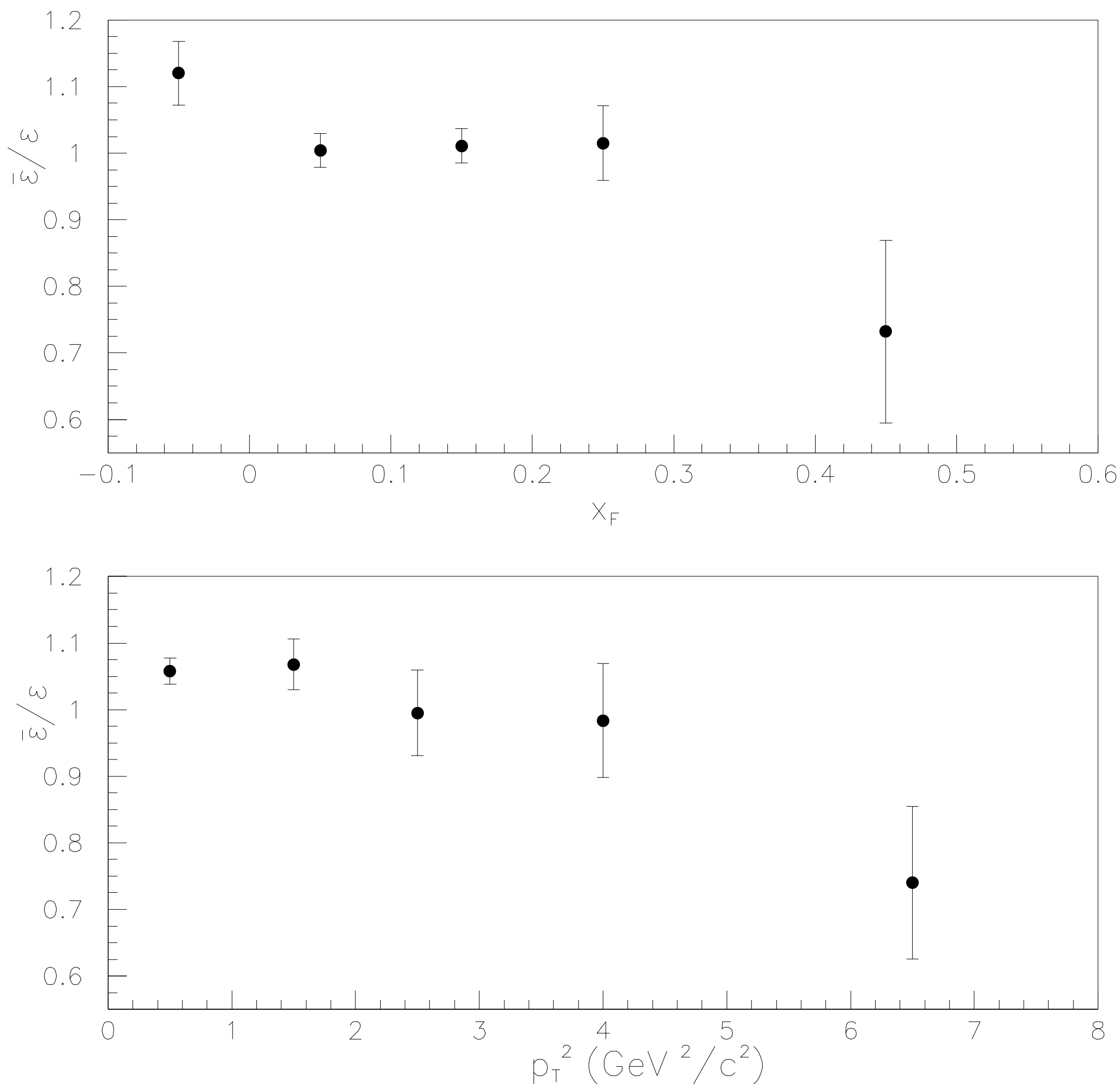
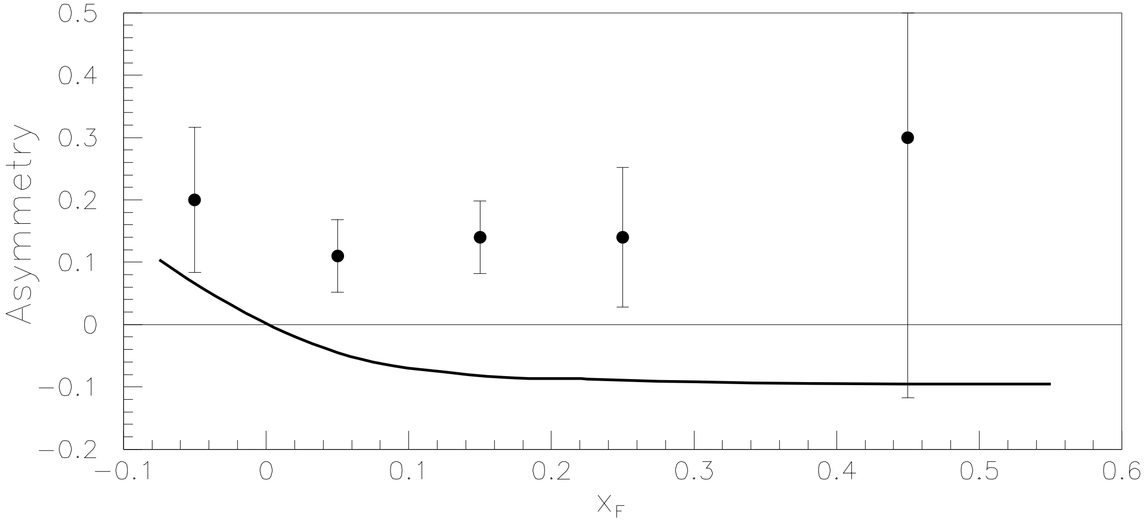


Figure 2. Λ_c^+ and Λ_c^- efficiency ratios, $\bar{\epsilon}/\epsilon$ as a function of x_F (upper plot) and p_T^2 (lower plot). The efficiency ratios for x_F (p_T^2) are integrated over the p_T^2 (x_F) range of the data set.



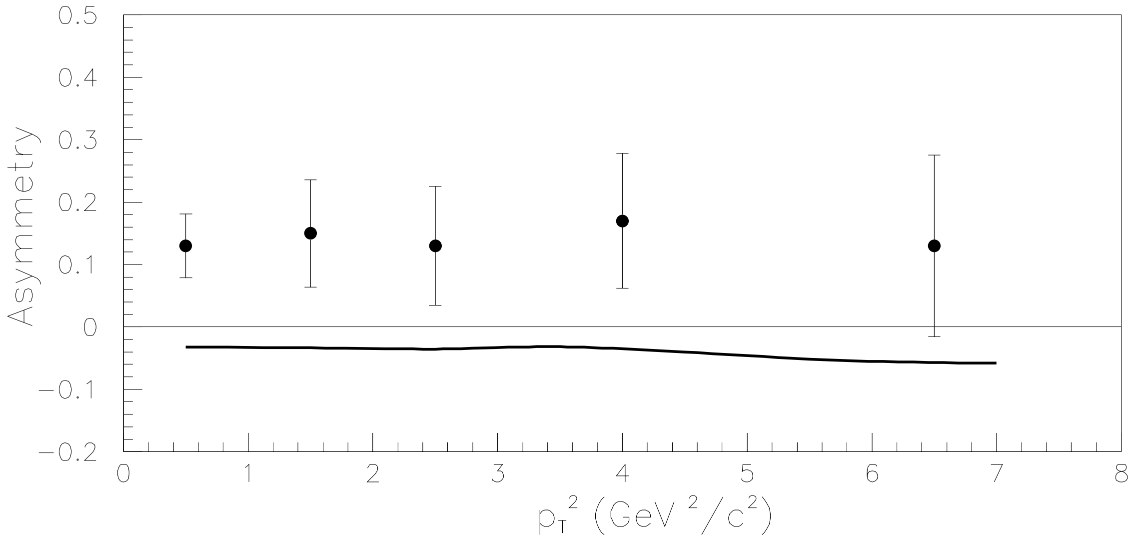


Figure 3. $\Lambda_c^+ - \Lambda_c^-$ asymmetry as a function of x_F (upper plot) and p_T^2 (lower plot). Full lines are the prediction of PYTHIA5.7/JETSET7.4 . The asymmetry for x_F (p_T^2) is integrated over the p_T^2 (x_F) range of the data set. Error bars show the statistical and systematic errors added in quadrature.

Table 1
Measured $\Lambda_c^+ - \Lambda_c^-$ asymmetry as a function of x_F and p_T^2.

x_F bin	Asymmetry	p_T^2 bin	Asymmetry
-0.1–0.0	$0.20 \pm 0.10 \pm 0.06$	0.0–1.0	$0.13 \pm 0.05 \pm 0.01$
0.0–0.1	$0.11 \pm 0.05 \pm 0.03$	1.0–2.0	$0.15 \pm 0.07 \pm 0.05$
0.1–0.2	$0.14 \pm 0.05 \pm 0.03$	2.0–3.0	$0.13 \pm 0.09 \pm 0.03$
0.2–0.3	$0.14 \pm 0.10 \pm 0.05$	3.0–5.0	$0.17 \pm 0.10 \pm 0.04$
0.3–0.6	$0.30 \pm 0.39 \pm 0.15$	5.0–8.0	$0.13 \pm 0.14 \pm 0.04$

Table 2
Comparison of the $\Lambda_c^+ - \Lambda_c^-$ asymmetries as measured by the E791, ACCMOR and SELEX Collaborations and predicted by three models. Experimental results in the $x_F > 0$ region are for different x_F ranges. See the text for details.

x_F region	E791	ACCMOR [10]	SELEX [9]	SF [2]	IC [3]	2CR [4]
$x_F < 0$	$0.20 \pm 0.10 \pm 0.06$	$--$	$--$	$+$	$+$	$+$
$x_F > 0$	$0.123 \pm 0.037 \pm 0.016$	0.005 ± 0.079	0.25 ± 0.15	$-$	0	0